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Life Cycle Assessment in Green Chemistry

A comparison of various industrial wood surface coatings

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Abstract

Background, Aims and Scope. Using renewable feedstock and introducing biocatalysts in the chemical industry have been suggested as the key strategies to reduce the environmental impact of chemicals. The Swedish interdisciplinary programme 'Greenchem', is aiming to develop these strategies. One target group of chemicals for Greenchem are wax esters which can be used in wood surface coatings for wood furniture, etc. The aim of this study was to conduct a life cycle assessment of four different wood surface coatings, two wax-based coatings and two lacquers using ultra violet light for hardening (UV lacquers). One of the two wax-based coatings is based on a renewable wax ester produced with biocatalysts from rapeseed oil, denoted 'green wax', while the other is based on fossil feedstock and is denoted 'fossil wax'. The two UV lacquers consist of one '100% UV' coating and one 'water-based UV' coating. The scope was to compare the environmental performance of the new 'green' coating with the three coatings which are on the market today.

Methods. The study has a cradle-to-grave perspective and the functional unit is 'decoration and protection of 1 m^2 wood table surface for 20 years'. Extensive data collection and calculations have been performed for the two wax-based coatings, whereas mainly existing LCI data have been used to characterise the production of the two UV lacquers.

Results. For all impact categories studied, the '100% UV' lacquer is the most environmentally benign alternative. The 'water-based UV' is the second best alternative for all impact categories except EP, where the 'fossil wax' is slightly better. For GWP the 'fossil wax' has the highest contribution followed by the 'green wax'. For AP and EP it is the 'green wax' that makes the highest environmental impact due to the contribution from the cultivation of the rapeseed and the production of the rapeseed oil. For POCP the 'fossil wax' makes the highest contribution, slightly higher than the contribution from the 'green wax'. Also the energy requirements for the '100% UV' lacquer is much lower than for the other coatings. The results from the toxicological evaluation conducted in this study, which was restricted to include only the UV lacquers, are inconclusive, giving different results depending on the model chosen, EDIP97 or USES.

Discussion. The result in this study shows that the environmental benefits of using revewable feedstock and processes based on biocatalysis in the production of wax esters used in wood surface coatings are rather limited. This is due to the high environmental impact from other steps in the life cycle of the coating.

Conclusions. Overall the '100% UV' lacquer seems to be the best alternative from an environmental point of view. This study shows that the hot spots of the life cycle of the coatings are the production of the ingredients, but also the application and drying of the coatings. The toxicity assessment shows the need for the development of a new model, a model which finds common ground in order to overcome the current situation of diverging results of toxicity assessments. The results in this study also point to the importance of investigating the environmental performance of a product based on fossil or renewable feedstock from a life cycle perspective.

Recommendations and Perspectives. The results in this study show that an efficient way to improve the wood coating industry environmentally is to increase the utilization of UV lacquers that are 100% UV-based. These coatings can also be even further improved by introducing biocatalytic processes and producing epoxides and diacrylates from renewable raw material instead of the fossil-based ones produced with conventional chemical methods in use today. In doing this, however, choosing a vegetable oil with good environmental performance is important. An alternative application of the 'green wax' analysed in this study may be as an ingredient in health care products, for example, which may result in greater environmental benefits than when the wax is used in wood coating products. The results in this study illustrate the importance of investigating the environmental performance of a product from cradle-to-grave perspective and not consider it 'green' because it is based on renewable resources.

Keywords: Biocatalyst; environmental impact; life cycle assessment; renewable feedstock; toxicity; UV lacquers; waxes; wood coating products

Introduction

The research programme 'Speciality Chemicals from Renewable Resources – Greenchem' is a Swedish interdisciplinary research programme which focuses on the development and application of biocatalysts in the production of fine chemical products from renewable raw materials. The programme includes research activities both within biotechnology and environmental systems analysis, and cooperates with several industrial partners, from raw material producers to end-use industry. One target chemical in the programme is wax esters for wood surface coatings based on vegetable oil (rapeseed oil) and produced by biocatalytic processes. The wood surface coatings are manufactured by the coating producer Akzo Nobel Industrial Wood Coatings and are utilised by IKEA on some of their wood furniture.

In this paper, four different wood surface coatings are analysed from an environmental point of view and a life cycle perspective. The coating products are one wax ester-based (the new 'green' coating), one paraffin wax-based coating and two lacquer coatings produced from fossil feedstock and by conventional chemical processes. These last three reference products are on the market today. The lacquers, for which ultra violet light is used for hardening (called UV lacquers), are here estimated to represent the best varnish-based wood coatings available today from an environmental point of view. The environmental impact of UV lacquers is significantly lower than, for example, of traditional lacquers using organic solvents. Another aim of this paper is to identify the steps of the life cycle which give rise to the most significant environmental impact (hot spots) in the systems studied, and to suggest improvements to the systems.

1 Methodology

Life cycle assessment (LCA) is a methodology for examining the environmental impact associated with a product from 'cradle to grave' – from the production of the raw materials to the ultimate disposal of waste. The LCA in this paper follows the methodology standardised in the ISO 14040-43 [1].

1.1 Goal of the study

The objectives of the investigation were; to compare four different surface coatings used on wood furniture, from an environmental point of view and a life cycle perspective; to identify the steps of the life cycle which have the greatest environmental impact, that is, hot spots, and to propose improvements and optimise the systems. The study is based mainly on the production conditions at Akzo Nobel Industrial Wood Coatings A/S in Copenhagen, and the application of the coatings is assumed to take place in Goleniow, Poland, at IKEA's factory for wood furniture. Thus, the results should not be utilised for any far-reaching conclusions concerning the environmental performance of UV lacquers and wax-based coatings in general.

1.2 The products investigated

The products investigated are two wax-based coatings and two UV lacquers. The wax-based coatings represent a group of products which are often promoted as more 'natural based' or 'environmentally benign' than traditional lacquers. The first coating is based on a wax ester, behenyl behenate, produced from rapeseed oil by biotechnological methods using biocatalysts (enzymes), hereafter denoted '*green wax*'. This coating is not commercially available today. However, the second wax coating is based on paraffin wax made from crude oil and produced by state-of-the-art technology using conventional chemical methods, hereafter denoted '*fossil wax*'. This product is on the market today. The two wax-based coatings have a dry content of approximately 20%, of which 60% is wax and 40% is acrylate. Also small amounts of additives, for example anti-foaming agents and biocides, are included in the wax coatings. The UV lacquers are based on a binder and contains solvent, anti-foaming agents, thickening agents and a photo inhibitor. The UV lacquers are hardened by ultra violet (UV) light after application on the wooden surface. The UV lacquers are produced from fossil oil by state-of-the art technology. The UV lacquers are here assumed to represent lacquers with the best environmental performance on the market today. One of the UV lacquers is water-based and is hereafter denoted '*water-based UV*', whereas the other is in dry form, and hereafter denoted '*100% UV*'. The 100% UV lacquer is a coating in a very dry form and therefore small amounts is needed per square meter. For the wax based coating almost 9 times as much is needed per square meter, and for the water based UV lacquer almost 15 times more is needed per square meter since it has high water content.

1.3 Functional unit

The functional unit is the definition of the functional outputs of the product system and provides a reference to which the inputs and outputs can be related. For this study, the functional unit is defined as: *decoration and protection of 1 m² wood table surface for 20 years*.

Based on standardized practical tests of the durability of the four different coatings on wood table surfaces carried out by Akzo Nobel Industrial Coatings AB in Malmö, Sweden [2], the life time of a treatment using UV lacquers is estimated to be 20 years. However, the life time of a treatment using wax-based coatings is estimated to be only 5 years. Thus, to achieve an equivalent function, the use of wax-based coatings on wood table surfaces is here taken to be four times that of UV lacquers. In the sensitivity analysis the result will be shown for the different coatings without the time aspect being taken into account, just to show the importance that this is done correctly in the functional unit.

In a study by Petersson et al. [3] an evaluation of different wax esters, among others, behenyl behenate, as an ingredient in wood coatings was conducted. The result showed that the 'green wax' coating has a good resistance to water, almost as good as the product existing today, i.e., the '*fossil wax*'. However, resistance to fat was relatively poor. The UV lacquers, however, have a very good resistance to both water and fat [2].

1.4 Allocation

When a production process contributes to several products, the total environmental load of the system has to be shared between these various products by allocation. Several methods can be used for allocation in LCA, such as physical and economic allocation. In this study physical allocation is used. The allocations made are in the refining of crude oil from which paraffin wax and other petroleum raw materials are produced, in the production of rapeseed oil from which also meal used as fodder is produced and in the product manufacturing of the various UV lacquers.

1.5 System description, calculation assumptions and input data

The systems investigated were divided into six subsystems; production of ingredients (1), product manufacture (2), packaging (3), transport (4), application (5) and disposal (6).

Inventory data for the wax-based coatings are taken from Gustafsson and Börjesson [7], Akzo Nobel Industrial Coatings AB [2] and based on our own calculations. Inventory data for the two lacquers are taken from Dreyer and Niemann [8]. The different ingredients are transported to Copenhagen, Denmark, where the product is manufactured and the packaging of the coatings takes place. The coatings are then transported to Goleniow, Poland, for application on IKEA's furniture. Thereafter the products are transported to the final consumer, assumed to be in Sweden, where also the final incineration of the coatings is assumed to takes place. Efforts have been made throughout the study to use only the most recent data available in the literature, thus representing state-of-the-art technologies.

1.5.1 Production of ingredients

For the wax-based coatings, inventory data for the green wax ester, behenyl behenate, and the fossil-based wax, paraffin, are taken from Gustafsson and Börjesson [7] where a life cycle comparison of these two products are reported. In that article data are given in detail. The cultivation of rapeseed for the production of vegetable oil for the wax ester has been assumed to be carried out in the flatlands of Svealand in Central Sweden and the production of behenyl behenate has been assumed to take place at Aarhus Karlshamn (Karlshamn, Sweden). Data on rapeseed cultivation and rapeseed oil production are based on Bernesson [9], whereas data on wax ester production are based on our own calculations together with data from Bernesson [9] and Karlshamns [10]. For paraffin wax, inventory data were taken from Boustead [11]. The other ingredients in the wax-based coatings are produced in various European countries and inventory data for them have been collected from each supplier directly and then received from Akzo Nobel Industrial Coatings [2]. The rest of the inventory data needed for the wax-based coating was also collected from Akzo Nobel Industrial Coatings [2] and based on our own calculations. Life cycle inventory data for the 100% UV lacquer and the water-based UV lacquer were based on a comprehensive study conducted by Dreyer and Niemann [8]. These data were received directly from Akzo Nobel Industrial Coatings [2]. For all the coatings only ingredients that contribute by more than 1% of the total weight per functional unit were considered in the raw material phase. All ingredients were, however, considered in all other phases.

1.5.2 Product manufacturing

Life cycle inventory data concerning the manufacture of the final wax-based coatings were collected from Akzo Nobel Industrial Coatings [2]. The mixing of the lacquers is included in the manufacturing step. The energy requirements for the mixing of the different lacquers depend on the mixing time, where the 100% UV lacquer has the longest mixing time and the wax-based lacquers have the shortest. The lacquers are also filtered and filter usage is included in this step. The filter used is made of 78% polyester and 22% steel. Data for polyester are taken from Dreyer and Niemann [8] and data for steel are taken from Seppälä [12]. District heating of the industrial buildings and also the electricity for administration and ventilation is included in the product manufacturing step. An amount of 6 g of iron is used per litre lacquer, and this is also included. Water is used for sanitary needs and for cleaning the reactors. An amount of 9 g of dangerous waste and 14 g of burnable waste are the by-products for each litre of lacquer. The use of paper and carbon needed are calculated to 0.38 g per litre lacquer. The use of water, the amount of waste created and the use of paper and carbon is, however, not included in the study. Data on average Danish electricity and district heating are taken from Eltra et al. [13].

1.5.3 Packaging of the products

The 100% UV lacquer and the two wax-based coatings are packed in 20 litre metal buckets. The weight of one bucket is 1,646 g. The water-based UV lacquer is packed in a 1,000 litre IBC, made of 71 kg wood and 23.3 kg high density polyethylene (HDPE). Data for steel are taken from Sepällä [12]. Life cycle inventory data for wood are taken from 'Trätek' [14] and data for HDPE are from Association of Plastic Manufacturers Europe, APME [15].

1.5.4 Transportation of theproducts

This LCA includes all transportation in the entire life cycle of the products, from the producers of the various ingredients to the factory in Copenhagen, Denmark, from the various producers of the packaging materials and the filters to the factory, transport of the final product to the user, which is here assumed to be IKEA located in Goleniow, Poland, and from here to the final consumer, assumed to be located in the south of Sweden, in Älmhult. The transport from the final consumer to disposal has not been taken into account. Data for the emissions from transportation are taken from NMT [16].

1.5.5 Application and drying of the coatings

During the application and drying, only emissions from the energy consumption are included. No data were available on the emissions to air from the wax-based coatings during the application; therefore this has not been included in the study. However, in the toxicity assessment the emissions to air during application and drying from the two UV lacquers are included. The application of the coatings is assumed to take place in Goleniow, Poland, where IKEA's factory is located. Therefore Polish electricity average data have been used for this step [17,18,19]. The electricity consumption for application and drying of the different lacquers is; 0.26 kWh/functional unit for the '100% UV' lacquer and 0.53 kWh/functional unit for the 'water-based UV' lacquer. For the two wax-based coatings the energy consumption is 0.53 KWh/m^2 per application, equivalent to 2.1 kWh/functional unit.

1.5.6 Disposal stage – waste incineration

The use of the furniture on which the coatings are applied has been assumed to take place in Sweden. The furniture on which the coatings are applied has been assumed to be incinerated after use. Therefore only calculations for the waste incineration of the coatings have been conducted. The waste

incineration has been assumed to take place in a combined heat and power plant and the emissions are calculated based on the composition of the different coatings, using an incineration model [20,21]. The potential impact of energy recovery is not included in the study.

1.6 Impact categories

The emissions to air included in this study are: CO_2 (carbon dioxide, fossil origin), CO (carbon monoxide), HC (hydrocarbons, except methane), CH_4 (methane), NO_X (nitrogen oxides), SO_X (sulphur oxides), NH_3 (ammonia), N_2O (nitrous oxide), and HCl (hydrochloric acid). Emissions to water include NO_3^- (nitrate). The environmental indicators and impact categories chosen are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical oxidant creation potential (POCP), and energy consumption. The category indicators for these impact categories are presented in **Table 1**.

A toxicological evaluation has been conducted comparing the two models EDIP97 and USES. Category indicators for EDIP97 are taken from Wenzel et al. [4] and characterisation factors for USES are taken from Huijbregts et al. [5]. The toxicological evaluation only includes the '100% UV' lacquer and the 'water-based UV' lacquer. The aim of this is not to come to any extensive conclusions about the toxicity for the lacquers but to compare the two models EDIP97 and CML2001 (also referred to as USES). EDIP97 (Environmental Design of Industrial Products 1997) is a Danish model while USES (Uniform System for Evaluation of Substances) is a Dutch model, both with a problem-oriented approach. The two models are not directly comparable, EDIP97 results being expressed as a volume of the end compartments while USES is expressed in 1,4-dichlorobenzene (1,4-DCB) equivalents. In Dreyer et al. [6] a model was presented to transform the results into the same type of figures for comparison. This model has also been used in this study. Furthermore, the same assumptions made when comparing the two models have been used. In the study by Dreyer et al. [6] life cycle inventory data for a water-based lacquer were used, which are the same as in this study. However, the functional unit is changed, the application and drying takes place at a different location and therefore also the transportation distances are different.

2 Results

The results for the coatings evaluated are shown in **Fig. 1**. An overall conclusion is that the 100% UV lacquer has the best environmental performance. Concerning the contribution to the GWP, the production of the ingredients has a greater environmental impact than all the other steps in the 'water-based UV' lacquer's entire life cycle. For the other coatings also the application and drying step and the disposal step make an important contribution to the GWP. The contribution to the GWP from the 100% UV lacquer is 8 to 9 times lower than from the other coatings.

Since the 'green wax' coating is based on a renewable resource, rapeseed oil, and the raw material in the 'fossil' wax is not, the contribution to global warming is higher for the 'fossil wax' when the disposal stage is included. The green wax, behenyl behenate used as ingredient in the coating 'green wax' has a slightly higher environmental load than paraffin wax, the wax used in the 'fossil wax' coating. In total the difference in contribution to global warming between the two coatings based on wax is very small.

For acidification, it is the two wax-based coatings that have the most significant environmental impact. Here it is also the application and drying step and the disposal step that contribute the most, because these two coatings contain small amount of sulphur which oxidizes to sulphur oxides (SO_X) when combusted. Here the 'green wax' has an environmental load almost eight times greater than the '100% UV' lacquer. A study of the production of the ingredients step for the 'fossil wax' and the 'green wax' shows that the 'green wax' has a contribution almost twice as high as the 'fossil wax' from this step. That is because the cultivation of rapeseed and production of rapeseed oil contribute quite markedly to the environmental load for this step. The same can be seen, even more clearly, for eutrophication, where the environmental load from the production of the ingredients

Table 1: Category indicators used in the study

	$GWP_{100\ years}$ g CO_2-eq/g	**AP g SO_2-eq/g**	**EP g PO_4^{3-}-eq/g**	**POCP g C_2H_2-eq/g**
Emissions to air				
CO_2	1	–	–	–
SO_X	–	1	–	–
NO_X	–	0.7	0.13	–
NH_3	–	1.88	0.35	–
CO	2	–	–	0.04
CH_4	23	–	–	0.007
HC		–	–	0.4
N_2O	296	–	–	–
HCl	–	0.88	–	–
Emissions to water				
NO_3^-	–	–	0.10	–

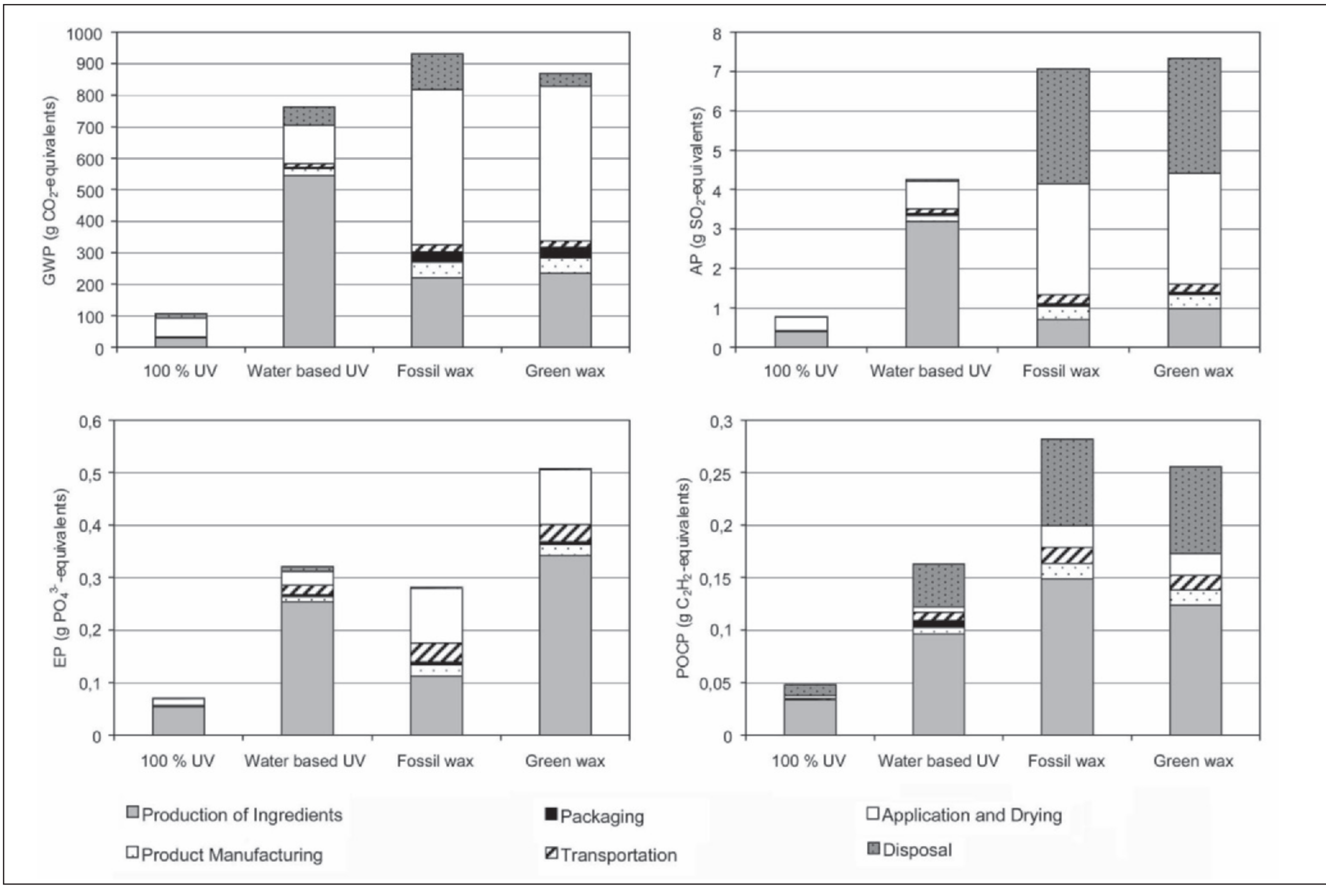

Fig. 1: The contribution to the global warming potential (GWP), to the acidification potential (AP), to the eutrophication potential (EP) and to the photochemical ozone creation potential (POCP) per functional unit for the wood coatings investigated

for the 'green wax' coating is almost three times higher than the load from the production of the ingredient step for the 'fossil wax'. For eutrophication it is the 'green wax' that has the highest load, followed by the 'water-based UV'. Here the large contribution from the 'green wax' comes from the cultivation and rapeseed oil production. This is due mainly to the use of fertilizers which give rise to leaching of NO_3^- to water [7]. Again it is the '100% UV' that has the best environmental performance; a contribution more than five times less than the 'green wax'.

For the photochemical ozone creation potential (POCP) the 'fossil wax' coating makes the largest contribution, slightly higher than the contribution from the 'green wax'. Here the '100% UV' lacquer is more than five times better than the wax-based coatings.

Overall, it can be seen that the amount of coating needed per functional unit plays a significant role in the total environmental performance of the coatings. The 'water-based UV' needs almost 10 times more lacquer to cover a given area than the '100% UV' coating and almost twice as much as the 'fossil wax' and the 'green wax' coatings.

In **Fig. 2** the energy requirements for the different coatings are shown. Here it is the '100% UV' coating that has the lowest energy requirements, followed by the 'green wax' coating. The 'water-based UV' has the highest energy requirement per functional unit, more than twice as much as the 'green wax' and more than 50 times higher than the '100% UV' lacquer. This is due to the high energy requirements for the production of the various ingredients and also for the application and drying step. Overall, the energy requirements for the different coatings are closely connected to the amount of coating needed per functional unit. The 'fossil wax' requires more energy than the 'green wax' since the production of paraffin requires more energy than the production of behenyl behenate.

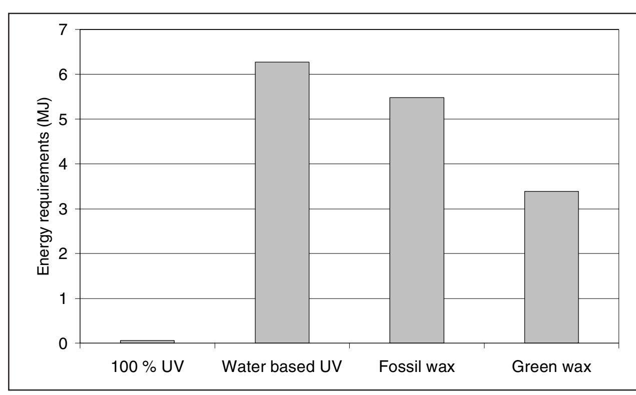

Fig. 2: The energy consumption in MJ per functional unit for the coatings investigated

2.1 Toxicological evaluation

For the two coatings the main contributors for human- and eco-toxicity are the same for the both methods. For the water-based UV lacquer the main contributors to human-toxicity, according to EDIP97, are ethylene glycol, nitrogen oxides and sulphur dioxide and for the 100% UV lacquer they are nitrogen oxides, chlorine and sulphur dioxide. The emission of ethylene glycol for the water-based UV lacquer comes mainly from the application and drying step. For USES the main contributors to human toxicity are chromium, arsenic and nickel for both lacquers. Overall the contribution to human-toxicity for the 100% UV lacquer is about ten times less than from the water-based UV lacquer. The human toxicity potentials for the two methods are shown in **Fig. 3**.

For eco-toxicity, opposite to the result for human-toxicity, the USES method scored much higher than EDIP97, 800 times higher on aquatic eco-toxicity in the study conducted by Dreyer et al. [6]. Here the main contributors differed between the two models. The main contributors in EDIP97 were strontium (to water), dioxin and chromium and the main contributors to USES were vanadium, nickel and selenium. In this study the main contributors to eco-toxicity also differ between the two models. For the water-based UV lacquer the main contributors to eco-toxicity, according to EDIP97, are iron (to water), strontium (to water) and chromium (to water) and for the 100% UV lacquer strontium (to water), iron (to water) and dioxin. The emissions of dioxin are higher for the 100% UV lacquer than for the water-based UV lacquer – which can be seen here. For USES the main contributors to eco-toxicity are vanadium, nickel (to air and water) and selenium for both lacquers. Also for eco-toxicity the performance of the 100% UV lacquer is better than the water-based UV lacquer, between 15 and 65 times, depending on the model. The eco-toxicity potentials based on the two models are shown in Fig. 3.

In **Table 2** the two models, EDIP97 and USES have been compared, the characterisation factors for EDIP97 have been

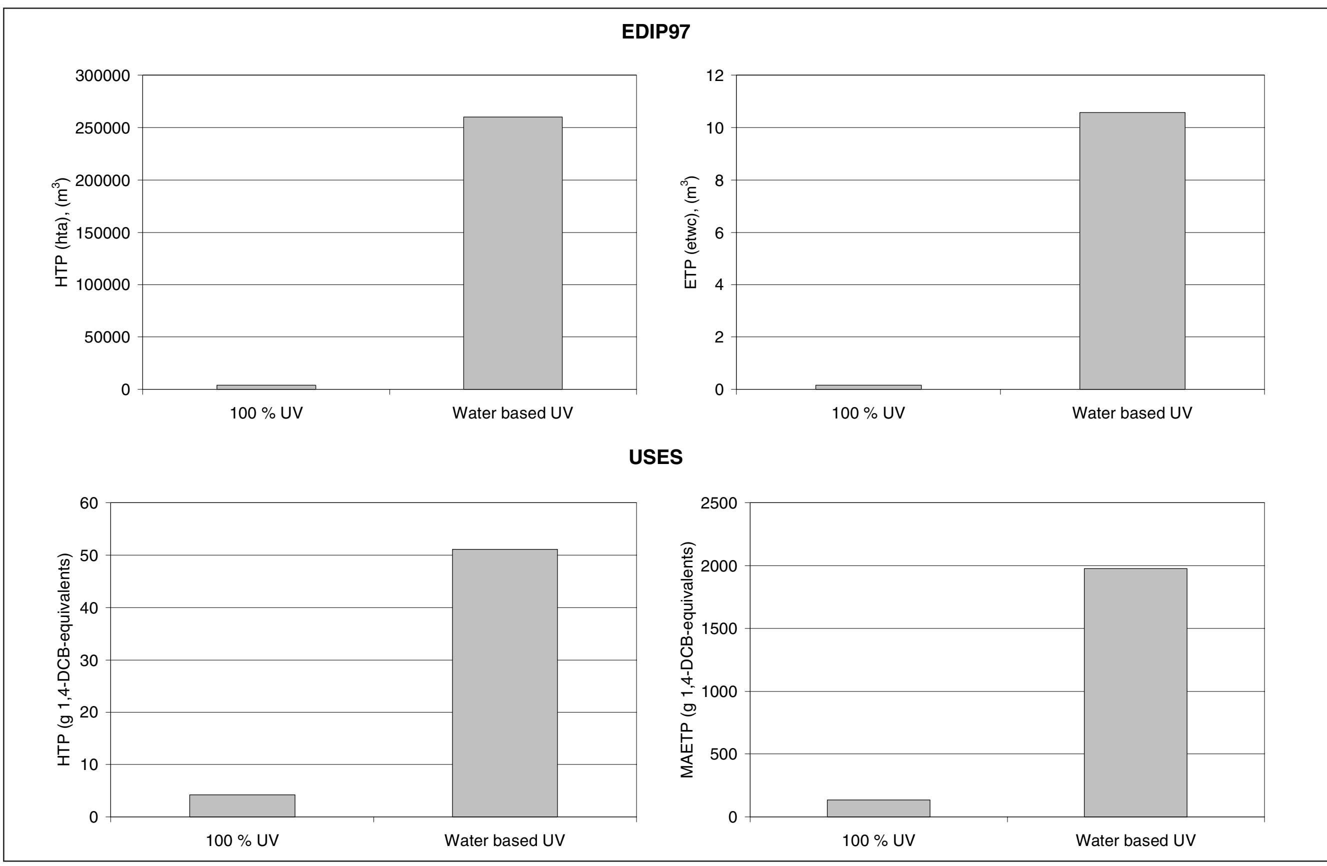

Fig. 3: The human- and eco-toxicity potential per functional unit for the '100% UV' lacquer and the 'water-based UV' lacquer per functional unit calculated with both the EDIP97 model and the USES model

Table 2: Comparison of EDIP97 and USES. For human-toxicity the contribution from air, water and soil for EDIP97 is aggregated and transformed into 1,4-DCB-equivalents. For eco-toxicity ETP (etwc) chronic toxicity in water is compared with USES marine waters subcategory (MAETP). All values are presented per functional unit

	Human-toxicity		Eco-toxicity	
	EDIP97 to USES g 1,4-DCB-eq	USES g 1,4-DCB-eq	EDIP97 to USES g 1,4-DCB-eq	USES g 1,4-DCB-eq
100% UV	4.0	4.2	0.33	130
Water-based UV	220	51	19	2,000

translated into units of a common reference substance, 1,4-dichlorobenzene (1,4-DCB), similar to what is done in USES. The result shows the inconclusiveness in the two methods. EDIP97 scores more than four times higher than USES for the water-based UV lacquer for human-toxicity, while the results for the 100% UV lacquer are similar for the two methods. However, the main contributors differ between the two models. For eco-toxicity the scores from the USES method is much higher, over a hundred times higher for the water-based UV lacquer and almost 400 times higher for the 100% UV lacquer, with also the main contributors differing in the models.

2.2 Sensitivity analysis

In **Fig. 4** the results are shown when the life time of the lacquers and wax coatings is assumed to be similar. Now the 'water-based UV' coating makes the greatest contribution to all the impact categories studied, while the wax-based coatings have a much better environmental performance. Thus, the setting of the life time of the various wood coatings has a significant impact on the results.

As concluded in the previous section, the application and drying step for the coatings makes a relatively large contribution to global warming. This is due to the fact that the coatings are applied in Poland where the electricity used is 98% coal-based. If the application and drying step was done in Sweden where electricity is 95% hydro- and nuclear-based, the emissions affecting global warming could be decreased. Furthermore, the transportation distances would be shorter. In the sensitivity analysis the effect of moving the application and drying step from Poland to Sweden (Älmhult) is shown, see **Fig. 5**. Data on Swedish electricity are taken from Uppenberg et al. [18,19]. It can be seen that this will decrease the total contribution to global warming by 16% ('water-based UV') and up to 57% ('green wax').

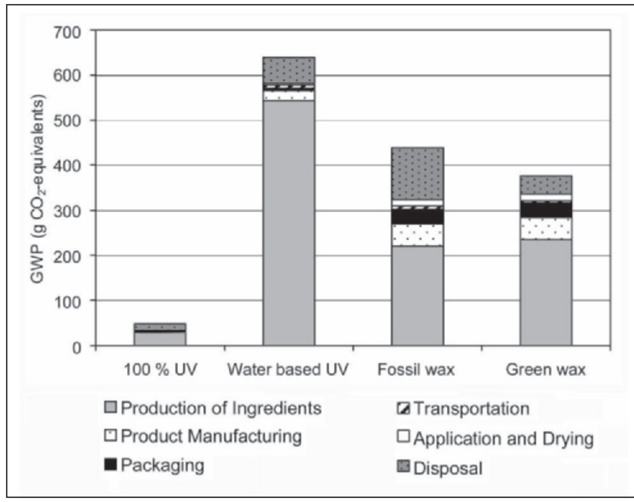

Fig. 5: Sensitivity analysis, the contribution to global warming per functional unit for the different coatings when application and drying of the coatings are moved to Älmhult, Sweden, using Swedish electricity that is based on 95% hydro and nuclear power. Also the transportation distances are changed

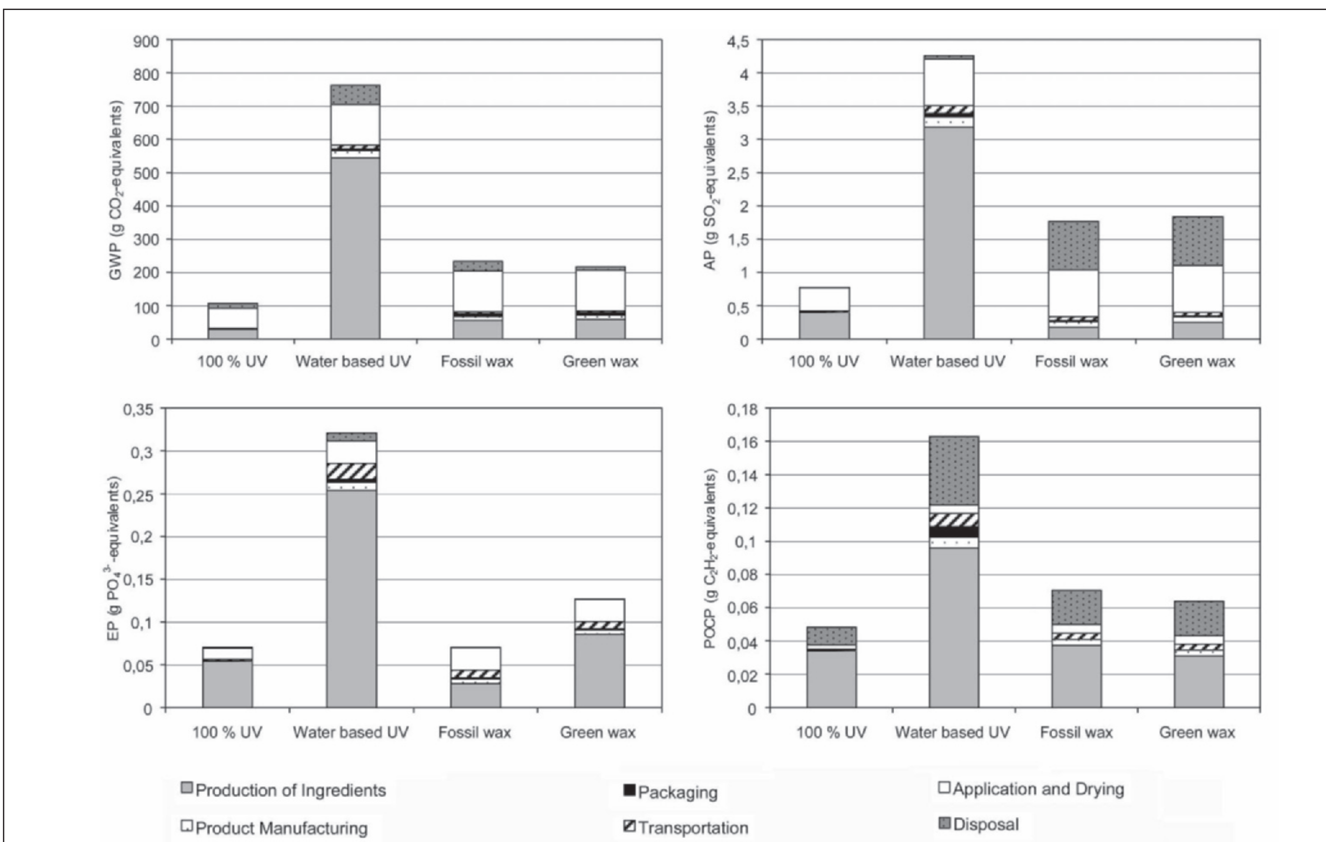

Fig. 4: The contribution to the global warming potential (GWP), to the acidification potential (AP), to the eutrophication potential (EP) and to the photochemical ozone creation potential (POCP) for the different wood coatings investigated when the life time of a treatment is not taken into consideration

The sensitivity in the production of the two wax-based coatings has been studied in Gustafsson and Börjesson [7]. Here the impact on the result by changing from economic to physical allocation for the production of behenyl behenate, the wax ester used in the 'green wax', is shown. Also the emissions from soil due to local conditions, the emissions of nitrous oxide (N_2O) from the production of fertilizers, the amount of fertilizer needed and the leaching of nitrogen from arable land was tested in the sensitivity analysis.

3 Discussion and Conclusions

For all impact categories studied the '100% UV' lacquer is the most environmentally benign alternative. The 'water-based UV' is the second best alternative for all impact categories with the exception of EP, where the 'fossil wax' is slightly better. For GWP the 'fossil wax' makes the highest contribution followed by the 'green wax'. This is due to the fact that the 'green wax' coating is based on a renewable resource and the 'fossil wax' is not, so therefore the contribution from the disposal stage is higher from the 'fossil wax'. For AP and EP it is the 'green wax' that has the highest environmental impact due to the contribution from the cultivation of rapeseed and the production of rapeseed oil. The use of fertilizers during cultivation leads to leaching of NO_3^- to water, affecting EP. For POCP the 'fossil wax' makes the highest contribution, slightly higher than the contribution from the 'green wax'. Also the energy requirements for the '100% UV' lacquer are much lower than for the other coatings.

This study shows that the hot spots of the life cycle of the coatings are the production of the ingredients, but also the application and drying. The best way to improve the wood coating industry environmentally is to change from water-based UV lacquers and from wax-based coatings to coatings that are 100% UV-based. These coatings can be even further improved by introducing epoxides and diacrylates from renewable raw material produced with biocatalysts instead of the fossil based ones, produced by conventional chemical methods that are on the market today. In doing this, however, choosing a vegetable oil more environmentally benign than rapeseed oil is important. Another way to improve the production is to move the application and drying step from Poland, where 98% of the electricity is based on coal, to Sweden with more environmentally benign electricity production [18,19].

Overall these results show the importance of taking the life time of the different coatings into consideration when comparing their environmental performance. This study also shows the importance of comparing the products investigated per square meter covered and not only via a functional unit showing the environmental performance per amount of coating. Here the '100% UV' lacquer has a higher environmental impact than the 'water-based UV' lacquer per litre, but since less than one tenth of the amount is needed per square metre, the overall environmental performance is better for the '100% UV'.

In this study the 'water-based UV' lacquer was compared with the '100% UV' lacquer from a toxicity point of view. The results of the toxicological calculations show the need for a new model which finds common ground to overcome the current situation of diverging results in toxicity assessments. The results found in this study are inconclusive, with different results depending on the model chosen, EDIP97 or USES. The main contributors also differ between the two models. For human-toxicity USES puts a stronger weight on metals while EDIP97 puts much stronger weight on ethylene glycol and nitrous oxides. For eco-toxicity the main contributors are more similar. Since the models at present are rather undependable the toxicological evaluation in this study includes only the two lacquers. It is not relevant to evaluate also the two wax-based coatings before a new method has been introduced. Far-reaching conclusions about UV lacquers can not be drawn from the results in this study, but the toxicological potential for the '100% UV' lacquer is much lower than for the 'water-based UV' lacquer with both methods. In Dreyer et al. [6] the inventory data for the water-based UV lacquer included in this study were used for an evaluation of different methods for evaluating toxicity, EDIP97 and USES (there called CML2001). The results for human-toxicity impact in that study showed that when using EDIP97 an impact score nearly five times higher than the score calculated with USES was found. This was most likely due to differences in the two methods. The result also showed that the human-toxicity potential was caused by different substances being assessed by the different methods, in the USES method mostly metals and in the EDIP97 method the main contributors were ethylene glycol and nitrogen oxides, the same as in this study. Overall the USES method put much greater weight on metals than the EDIP97 method.

LCA is, according to OECD [22], the best method for determining the increased degree of cleanness that can be achieved by introducing biotechnological processes. The wax ester used in the 'green wax' is produced in this way, using enzymes. A study conducted by Petersson et al. [3] shows that the biocatalytic production of the green wax ester consumes 34% less energy than the conventional chemical process. In Gustafsson and Börjesson [7] it is also shown that the production of 1 kilo of green wax ester consumes 3.5 times less energy than the production of 1 kilo of paraffin wax.

If the life time of a treatment of wax ester-based coating can be prolonged, as was shown in the sensitivity analysis, the wax-based coatings would be a more environmentally benign alternative than water-based UV lacquers. The wax ester used in the green coating can also be used as an ingredient instead of paraffin wax in many other applications, for example, in lotions and health care products, the reason being our finding that the 'green wax' was less environmentally benign than the 100% UV lacquer.

4 Recommendations and Perspectives

The results in this study show that an efficient way to improve the wood coating industry environmentally is to increase the utilization of UV lacquers that are 100% UV-based. These coatings can also be even further improved by introducing enzymes and producing epoxides and diacrylates from renewable raw material instead of the fossil-based ones

produced with conventional chemical methods used on the market today. Also the choice of the raw material is critical so as not to compromise the advantages gained by the biocatalytic process. If another raw material, instead of rapeseed oil, could be used for the 'green wax' maybe the environmental performance would be improved.

The need for the development of a new toxicity model may already be solved. At present, the European Union is deciding on the new chemical legislation, REACH (Registration, Evaluation and Authorisation of Chemicals), where LCA is pointed out as having a future role in chemical regulation. Here OMNIITOX and a newly developed model for toxicological evaluations will play an important role. The aim of the European project OMNIITOX (Operational Models aNd Information tools for Industrial applications of eco/TOXicological impact assessments) is to develop a method for evaluating toxicological effects in LCA and to provide characterisation factors for the most commonly used chemicals. With the developed 'Base Model' and 'Simple Base Model' calculated characteristics of a wide range of substances will be covered [23].

Utilization of natural renewable resources in the production of environmentally benign chemicals as substitutes for petroleum-based chemicals has attracted considerable attention over the past decade. Although some examples of biodegradable products, such as polymers are being reported, turning from petroleum-based to renewable resources as the starting material for chemicals represents a major challenge. Patel et al. [24] investigated the potential to save energy and reduce CO_2-emissions from the manufacture and use of plastics and other fossil coal products in Germany, by increased recycling and by using bio-based raw materials. The results indicated significant potential savings compared with potential savings within the energy sector. However, it is not obvious that, for instance, biosynthetic polymers are always better than petrochemical polymers from an environmental point of view. Heyde [25], for example, showed that the total demand of non-renewable resources in biosynthetic polymer life cycles is in some specific cases higher than the demand in comparable petrochemical product life cycles. Also the results in this study illustrate the importance of investigating the environmental performance of a product from cradle-to-grave and not only consider it 'green' because it is based on renewable resources or is produced based on the principles of Green Chemistry [26].

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